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14. ABSTRACT

Bulk unrelaxed InAsSb alloys with Sb compositions up to 65% and layer thicknesses up to 3 ?m were grown by molecular beam epitaxy. The photoluminescence (PL) peak energy as low as 0.10 eV was demonstrated at T = 77 K. The electroluminescence and quantum efficiency data demonstrated with unoptimized barrier heterostructures from T = 80 to 150 K suggested large absorption and carrier lifetimes sufficient for the development of long wave infrared detectors and emitters with high quantum efficiency. The minority hole transport was found to be adequate for development of the

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Structural and Optical Characteristics of Metamorphic Bulk InAsSb

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Keywords: Metamorphic growth; unrelaxed InAsSb bulk; long-wave infrared; detector.

1. Introduction

Growth of $InAs_{1-x}Sb_x$–based epitaxial materials for infrared photodetectors has a long development history[1-2]. A strong energy gap bowing in these materials results in the smallest energy gaps available for III-V semiconductor compounds. However the development of InAsSb alloys was challenged by the large lattice mismatch between InAsSb and commercial available substrates. Earlier work reported the growth of relaxed InAsSb layers on various substrates[3-5]. Photoconductive detectors based on relaxed InAsSb grown on GaAs were demonstrated[6]. The relaxed InAsSb showed high dislocation densities and relatively broad photoluminescence spectra[7-8].

Recently, the number of publications devoted to the development of InAsSb-based materials has increased[9-20]. With the demonstrated advantage of the barrier detectors[13-14], the mid-wave infrared detector industry's interest has turned toward heterostructure detectors with bulk InAsSb absorbers and AlSb-based barriers. These structures can outperform InSb homojunction photodetectors operating at elevated temperatures. Compared with LWIR InAs/GaSb superlattices (SLS), undoped InAsSb bulk materials have a longer minority carrier lifetime[21-24]. In addition, bulk materials have higher absorption coefficients, resulting in higher quantum efficiency. Therefore, InAsSb-based materials are also gaining attention for the development of long-wave infrared (LWIR) photodetectors[25-29].

The development of bulk InAsSb alloys with Sb compositions up to 44% was demonstrated recently, using metamorphic growth[16]. The materials were grown on GaSb substrates with two types of buffers, GaInSb and AlInSb, utilizing linear grading of the buffer composition. The InAsSb layers were grown with a lattice constant equal to the lateral lattice constant at the top of the buffer layer resulting in a low residual strain (< 0.1%). Unrelaxed InAsSb alloys grown on graded buffer layers were found to have a random distribution of group V atoms (ordering-free)[18]. Analysis of electron diffraction patterns for InAsSb showed that ordering correlates with the presence of strain. The inherent energy gap for the bulk unstrained $InAsSb_{0.44}$ was found to be 120 meV at T = 13 K The nature of the strong bowing of the energy gap in InAsSb remains unclear, but it is not due to ordering or residual strain. Minority carrier lifetimes up to 350 ns at T = 77 K were reported for 1-μm-thick undoped bulk $InAsSb_{0.2}$ layers grown on metamorphic buffers[25]. In the present work, the bulk unrelaxed $InAsSb_{0.55}$ with photoluminescence peak wavelength as long as 12.4 μm at 77 K μm is demonstrated. The heterostructures for study of LWIR detection are designed and fabricated. The results show high quantum efficiency and efficient hole transport.

2. Material and Growth Characterization

The heterostructures were grown on GaSb substrates by solid-source molecular beam epitaxy (MBE) utilizing valved crackers for As and Sb. The substrate temperature was controlled by a pyrometer that was previously calibrated using references such as the III to V enriched surface reconstruction transition, oxide desorption and melting point of InSb. The growth temperature was maintained near 415 ^{0}C for the InAsSb layers. The growth rate was about 1 μm per hour. The Sb incorporation was adjusted by the relatives pressure of As and Sb as measured by a beam-flux-monitor. The compositionally graded buffer layers were up to 3.5 μm thick and grown at elevated temperatures ranging from 460 to 520 ^{0}C. In this work GaInSb buffer layers with linear composition grading were used with the lattice constant increase rate ranging from 0.5 to 0.8% per micron. The native (without strain distortion) lattice constant of the top of the buffer was 1.2-1.3% greater that the target lateral lattice constant. For GaInSb buffers this approach was implemented in Ref. 26.

Figure 1 shows a cross-sectional (220) bright field TEM image of the $InAs_{0.8}Sb_{0.2}$ bulk layer grown on a GaInSb graded buffer. No dislocations can be seen at this resolution in the epi-structure containing the $InAs_{0.8}Sb_{0.2}$ bulk layer. The long dislocation lines seen in the lower part of the buffer layers are aligned along the [110] direction, indicating efficient dislocation glide in the graded buffer. The topmost portion of the graded buffer remained unrelaxed under small compressive strain. The bulk InAsSb layers were grown nearly lattice matched to the in-plane lattice constants of the topmost of the strained section of the buffers. No evidence of long-range CuPt-type ordering was observed in electron diffraction patterns obtained with transmission electron microscopy[18].

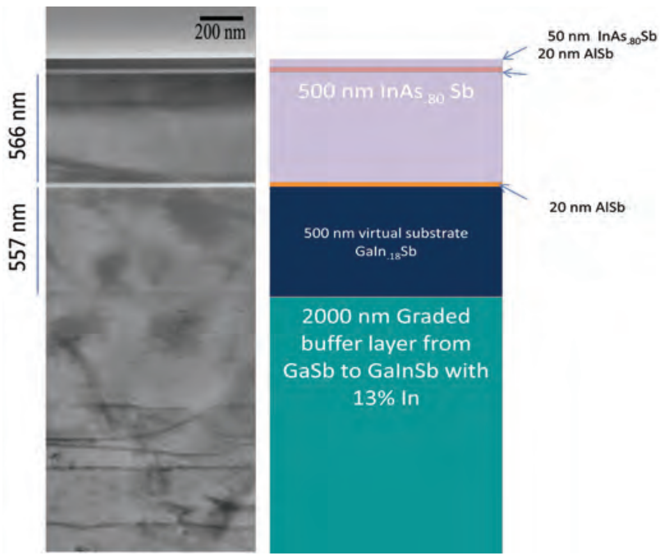


Fig. 1. XTEM image (220 bright field with two beam condition) of the metamorphic structure with 0.5-μm thick InAs0.8Sb0.2 bulk layer grown on GaInSb graded buffer.

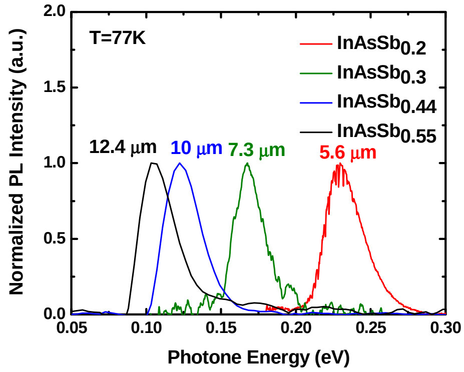


Fig. 2. Asymmetric (335) RSM taken at azimuth angle equal to 90 for $InAsSb_{0.4}$ layer grown on the top of GaInSb buffer. The color bar shows the relative counts in logarithmic scale.

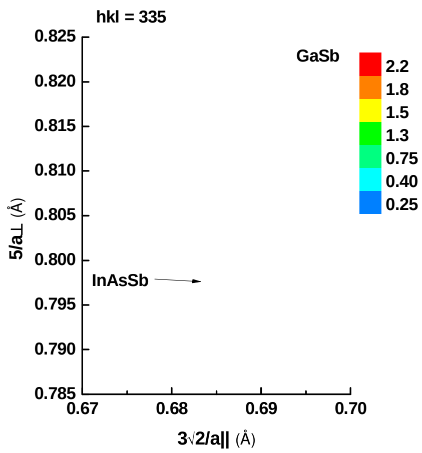


Fig. 3. The normalized PL spectra for InAsSb bulk with different Sb compositions at 77 K. (20% red line, 30% green line, 44% blue line, 55% black line)

The PL spectra were measured with a Fourier-transform infrared (FTIR) spectrometer equipped with a HgCdTe detector (14 μm cutoff wavelength). The PL was excited by a 1064 nm solid-state laser and was collected by reflective optics. The PL spectra were obtained with excitation powers of 100 mW. The excitation area was 1.2×10^{-3} cm^2. Figure 3 shows the normalized PL spectra of the bulk InAsSb alloys with different Sb composition measured at T = 77 K. The longest wavelength of 12.4 μm with a Sb composition 55% was demonstrated. It is the longest peak wavelength ever reported from group III-V bulk alloys.

The PL data obtained for recently grown InAsSb layers with large Sb compositions were used for updating the value of the bowing parameter reported in the earlier publication[16]. Fitting the dependence of the PL peak wavelength on Sb composition with data for older and recently grown bulk InAsSb (Figure 4) is consistent with the energy gap bowing parameter of 0.87 eV reported in[18,28].

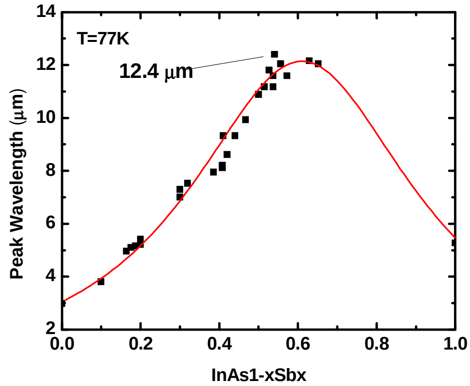
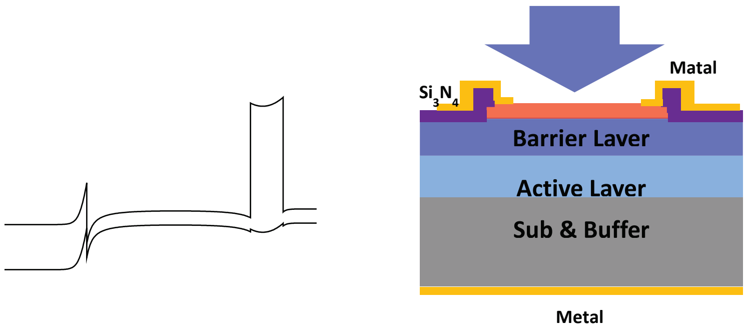


Fig. 4. The dependence of PL peak wavelength versus Sb composition for bulk InAsSb measured at T = 77 K. The best fit was obtained with the bowing parameter of 0.87 eV.

3. Barrier Detectors for Long Wave Infrared Range

We assessed the feasibility of the similar barrier heterostructures with bulk InAsSb alloys for the LWIR detector. The top contact layer doping was replaced with Tellurium to resemble nBn type barrier detectors. The undoped AlInAsSb barrier was grown lattice matched to InAsSb with 40% Sb composition. The schematic band diagram of the heterostructure under bias is shown in Figure 5a.



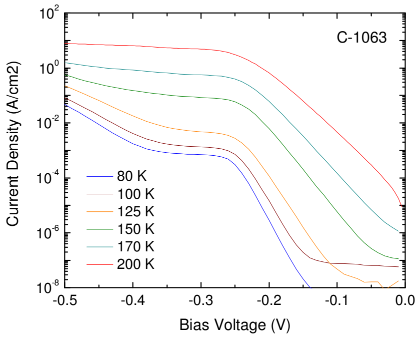
(a) (b)

Fig. 5. (a) The schematic band diagram for the heterostructure with a bulk InAsSb absorber with 44% of Sb composition. The AlInSb barrier was lattice-matched to the InAsSb absorber layer. The top contact layer was doped with Tellurium to a level of n = 1×10^{18} cm^{-3}. (b) The schematic cross-section of the processed heterostructures for LWIR detector with top illumination.

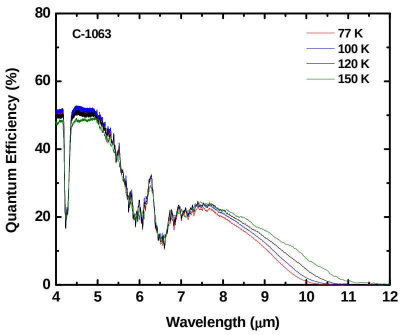
The heterostructures were processed with a window for incident radiation on top of the epilayer. The window opening was a square with a 250-μm side. The top metal contact layer was a square with a 300-μm size. The InAsSb contact layer outside the metal contact was removed down to the barrier layer by reactive ion etching. Silicon Nitride was used for isolation. No coating was deposited. The schematic device cross-section view in shown in Figure 5b.

The external quantum efficiency (QE) spectra were obtained with FTIR spectrometry. The absolute values of the responsivity and the quantum efficiency, respectively, were obtained using a black body with the temperature of 800 °C.

The nBn requires negative DC bias applied to the top of the epi-layer contact to suppress the AlInAsSb barrier for holes. The QE was increasing with bias until it reaches a constant level for a bias of -0.4 V. The QE spectra in Figure 9a. are presented for the bias voltage of - 0.4 V for the temperatures from 80 to 150 K. The distortion of the QE spectra between λ = 5.5 and 8 µm are explained by atmospheric absorption. The QE increases monotonically with photon energy from λ= 10 µm at T = 80 K and from λ = 11 µm at T = 150 K. The absolute values of QE in the long wave infrared range are relatively high considering the incomplete absorption in the relatively thin absorber. An increase of QE with temperature from T = 80 to 150 K at a particular wavelength is likely due to the red shift of the energy gap with temperature. It showed that the carrier lifetime is not limited by Auger recombination, in addition the diffusion length is sufficiently large compared to the absorber thickness and the QE is not limited by hole transport. It was concluded that QE for the long-wave infrared photodetectors based on the bulk InAsSb layers should benefit from an increase of the absorber thickness.



(a)



(b)

Fig. 6. (a) The IV characteristics obtained for heterostructures with a 1-µm-thick InAsSb layers with Sb composition of 40% at different temperatures ranging from 80 K to 200 K. (b) The spectra of external quantum efficiency obtained for the heterostructures with a 1-µm-thick InAsSb layers with Sb composition of 40% at the temperatures of 77 K, 100 K, 120 K, and 150 K, respectively.

The IV characteristics of InAsSb heterostrucutres measured from 80 K to 200 K under dark conditions are shown in Figure 9b. The bias was defined with respect to top epi-layer contact. The IV characteristics show that the dark current was nearly constant from -0.25 V to -0.4 V, in which region the QE increases and saturates. This could be explained by the dark current being diffusion limited. Once the barrier for minority holes was suppressed, holes in the active layer could diffuse to the top contact. It also indicates good valance band alignment between the absorber and barrier layer.

We can conclude that the barrier heterostructures with a 1-µm-thick bulk $InAsSb_{0.4}$ layer showed adequate light absorption and transport of minority holes across the absorber.

The QE should benefit from increased absorber layer thicknesses. In order to prove that and get larger quantum efficiency, similar heterostructures with thicker $InAsSb_{0.5}$ absorber layer were grown and fabricated. Figure 7 shows QE measurements for different active layer thickness at 77K. With a $InAsSb_{0.5}$ absorber layer, the cutoff wavelength extends to 11 μm for all three devices. QE at 8 μm increases from 23% to 39%, with the absorber thickness increasing from 1 μm to 3 μm. We assume the photo-generated carriers in the active layer were proportional to $I_0(1-\exp(-\alpha * L)$, where I_0 is the incident light intensity, α is the absorption coefficient at certain wavelength, and L is the thickness of active layer. The data presented indicates an absorption coefficient of 3500 cm^{-1} at $\lambda = 8$ μm. Meanwhile it shows that the diffusion length is larger than 3 μm, and the InAsSb based LWIR detector could potentially have increased QE for thicker absorber layers.

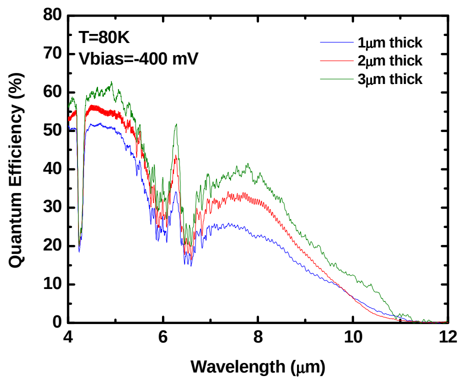


Fig. 7. The spectra of external quantum efficiency obtained for the heterostructures of $InAsSb_{0.5}$ layers at 77 K with different active layer thickness. 1 μm (blue line), 2 μm (red line), 3 μm (green line)

4. Summary

It was demonstrated that the bulk InAsSb materials free of group-V ordering grown on metamorphic buffers are capable of encompassing the long wave infrared range at low temperatures. The longest PL peak wavelength of group III-V alloys (12.4 μm) at 77 K was shown. The characterization data obtained for unoptimized heterostructures suggests sufficiently large absorption and carrier lifetimes (long diffusion length) suitable for the development of infrared. The carrier transport, including the transport of minority holes, is adequate for the development of detectors and emitters with increased active layer thickness.

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